SOIL BIN STUDIES

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R.N. Yong, R.D. Japp and S.J. Windisch

Report to
Cornell Aeronautical Laboratory, Inc.
Contract S-68-5

Sponsored by
Advanced Research Projects Agency
Project AGILE
Department of Defense
ARPA Order No. 841 dated 7 May 1966

SOIL MECHANICS LABORATORY

McGILL UNIVERSITY

DEPARTMENT OF CIVIL ENGINEERING AND APPLIED MECHANICS

MONTREAL, CANADA

49

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PREFACE

The following is one of two closing out contract reports for work performed under Cornell Aeronautical Laboratories Contract No. S-68-5 and supports the Soil Mechanics Task of the Off-Road Mobility Research (ORMR) for which Cornell Aeronautical Laboratories is the prime contractor and is sponsored by the Advanced Research Projects Project AGILE, Department of Defense, and MONITORED [redacted] by the United States Army Research Office, Durham, under Contract No. DAHC04-67-C-0005.

These two reports are "Soil Bin Studies" and "Soil Water Relationships and Their Engineering Applications". The intent of the overall contract for Cornell Aeronautical Laboratories was to provide input information for application of the visioplasticity method of analysis for soil-vehicle interaction. In addition soil fabric studies were performed to assess the feasibility of applications of energy methods of analysis.

The study was performed during the period November 1967 to September 1968 under the guidance of Mr. George Bartlett, ORMR Program Manager and Mr. Paul Rosenthal and Dr. Patrick Miller, CAL ORMR Soil Mechanics Task Leaders. Mr. A.N. Tedesco was ARPA Technical Monitor.

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SECTION 1 - PRELIMINARY CONSIDERATIONS

1.1 INTRODUCTION

The problem of determining wheel-soil interaction is part of the overall problem of soil vehicle mechanics. From the practical standpoint this is the field of mobility and trafficability. Unfortunately, up until the present time, more attention has been focussed on mechanical aspects of the vehicle and its relationship to soil. There has not been sufficient attention paid to the soil response to the moving vehicle, be it tracks or wheels. Thus it is seen that although a considerable amount of research can be performed on this problem, it is doubtful if meaningfull answers can really be achieved, if little attention is paid to the soil component of the overall problem.

To be sure one can obtain an adequate and probably satisfactory solution to the problem by superficially assessing the effects of soil behaviour and considering only very gross bulk parameters in soils. However, the problem still revolves around an understanding of the behaviour of soil with respect to the whole system. What needs to be considered in essence, is a passive system wherein the response is dependent in part on the input to the torque applied, and the output modified through passive soil behaviour accordingly will provide one with an evaluation of the drawbar pull realized. This in essence is the criterion used for assessing the performance and adequacy of vehicles in general.

1.2 STATEMENT OF THE PROBLEM

The problem itself whilst it is large can be reduced to very simple terms if one wishes to examine this in greater detail. As a start it is necessary therefore to establish the stress and strain rate fields beneath the moving contact surface. In order to simplify considerations, this study report deals with experiments performed on rigid wheels and their relationship to soil.

Since it has been established that it is not feasible to measure stresses or pressures within the soil because of the doubtful integrity of the gauges required in this kind of a program, the cold flash X-ray procedure is used to establish the time-displacement of representative particles within the soil. Reference is made to the reports (Soil Mechanics Series No. 20, 22, and 23) published by the Soil Mechanics Laboratory of McGill University. The problems expected in soil testing, whether it is for soil vehicle work or for other purposes, centres around the ability of the investigator to obtain reproducible samples - and how well these samples represent the real system. In this particular problem, attention was directed towards obtaining as best as possible a sensible field of target markers in the soil in order that the data obtained could be used for analysis (utilizing the visioplasicity method).

Whilst deviations from a sensible array of lead markers can be tolerated, it is expected that these should be minimized since the analytical smoothing techniques required would provide greater accuracy in utilization of test results. It must however by emphasized that by

itself accuracy in reduction of test data is completely meaningless if no appreciation of the physical properties of the soil and their relationships to actual field situation is considered. In general since it is fairly well understood that the soils fabricated in laboratories bear little relationship to field soils where natural bonds do exist, the problem of remoulded soils by itself is one which creates and relegates itself to a very special class of problems. In the field condition, it is to be understood that near the surface, because of the problems of evaporation and evapo-transpiration, few soils are completely saturated. If we are to examine the problem of soil vehicle interaction, consideration of fully saturated remoulded soils seems to create a situation similar to one of wishful thought. Whilst the special case of fully saturated soils provides one with a much easier solution to the problem, in actual fact this is a particular solution.

In view of the problems of soil placement in the testing bin, it has not been feasible in this study to obtain a fully saturated soil consolidated to the particular density desired under the test wheel. In order to obtain full saturation and to provide consolidation to achieve the desired density, it would have been necessary to consolidate slurried samples in the soil bin itself. The test section has been described previously in Soil Mechanics Reports No. 20, 22 and 23, and it will be seen that in view of the time required to achieve 90% consolidation (using information from standard consolidation tests)

the time to prepare a sample from slurry and to consolidate it to the desired density in the test would be in the order of three to six months. Consequently it does not seem feasible to provide samples in this fashion within the time available and under the terms of reference of soil investigation under the moving wheel. It therefore appears that the only solution to the problem where several test series are examined under various conditions imposed by the moving wheel, a remoulded partially saturated soil condition must be tolerated. The difficulties arising therefrom are large because of the partially remoulded state, and centre around the requirements for reproducibility in terms of fabric, structure, water content distribution, etc. The former two requirements are not well assessed and it was therefore decided to achieve as best as possible a uniform water content distribution within the test bin.

1.3 REPORT ORGANIZATION

This report is broken up into two parts. The first part concerns itself with the driven wheels whereby the specifications for the wheel input into the soil etc. were essentially those arrived at in consultation and agreement with Cornell Aeronautical Laboratory. The exposed X-ray plates taken immediately after the soil-wheel test were developed and send down immediately to CAL. No requirement was imposed on the production of data since it was not possible to pursue production of data in view of the requirements for X-ray plates being transmitted to CAL. However, other pieces of information concerning

soil properties and above ground parameters were obtained and these are reported in Section 2. A detailed procedure for sampling, etc., are shown in Section 2 together with a brief survey of the experimental difficulties one might encounter with such a program. The summary of the tests conducted and the details are self evident.

In Section 3 a series of towed wheel tests were conducted on the initiative of the research staff at McGill with a view to obtaining, for a particular case, as complete as possible information that may be used in the analysis being developed at Cornell Aeronautical Laboratories. The form of the analysis centres around the visio-plasticity technique which is similar to the one developed earlier at McGill University (Yong and Osler, 1966). Thus there will be seen the tabular results for strain-rate fields.

SECTION 2 - DRIVEN WHEEL TESTS

2.1 INTRODUCTION

The driven wheel program consisted of a series of nineteen tests conducted on one soil type, namely a remoulded kaolin. The specifications for these tests were established by C.A.L. The exposed X-ray plates denoting soil marker positions at various stages of the transient loading obtained during the above tests, together with a record of measured test parameters, were sent directly to C.A.L. to provide inputs for their analysis. The driven wheel tests were supplemented by additional testing of the soil in the form of unconsolidated, undrained conventional triaxial tests on cylindrical specimens for strength evaluation, true triaxial tests on prismatic specimens, moisture content determinations, and laboratory vane shear tests. The results of these tests have also been previously forwarded to C.A.L.

The work concerned with fabric distortion and evaluation required a more detailed examination of the fundamental aspects of the problem. Because of the difficulties and aspects involved, it has been found more convenient to present this in a separate report.

2.2 THE EXPERIMENTAL FACILITY

The soil-wheel experimental facility of the McGill Soil Mechanics Laboratory consists of six major components which are as

follows: The soil bin, the wheel and wheel support unit, the hydraulic carriage drive, the electric wheel drive, the flash X-ray unit and the recording system. The basic system has been described in detail in Yong et al (1967). The modified system used in clay studies (and in this present study) has been reported in Yong et al (1968). A schematic diagram of the test facility is shown in Figure 2.1.

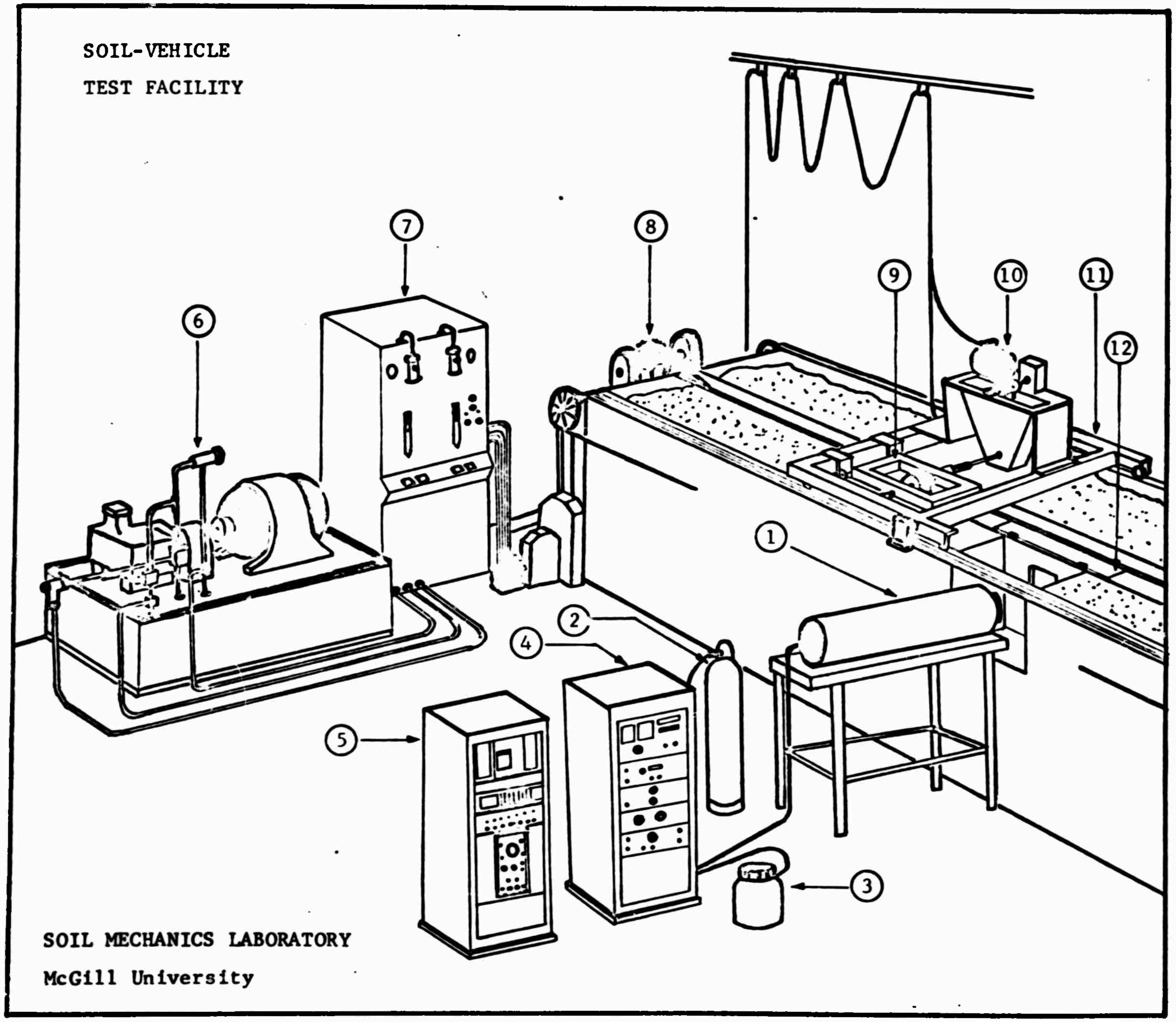
2.2.1 The Soil Bin

The driven wheel series of experiments utilized a test section of soil approximately 4 inches wide by 6 feet long and 2 feet deep. The major function of the large soil bin was to provide support for the sample holder, dynamometer carriage rails, mobile cassette holder, and the flash X-ray pulser.

2.2.2 Wheel and Wheel Support Unit

Two polished aluminum wheels were used for the experiments performed in the contract program. These wheels were 6.75 inches and 4.50 inches in radius and had widths of 3.75 inches and 2.50 inches respectively and were therefore similar with respect to aspect ratio. The geometric scaling ratio between the two wheels is 3/2.

The selected test wheel was mounted on a light weight adjustable aluminum flexure frame attached to the dynamometer carriage through two instrumented flexure pivots. The deflection of the flexural pivots, monitored by bonded strain gauge circuits, provided a measure of the drawbar pull. A torque measuring device was placed



(1) 300 kv pulser containing X-ray tube
(2) Nitrogen tank
(3) Freon tank
(4) Power supply, trigger amplifier and selector, gas pressure controls for X-ray unit
(5) U.V. recorder, amplifiers
(6) Hydraulic pump unit.
(7) Hydraulic control panel
(8) Chain drive for mobile cassette holder
(9) Flexure frame, wheel under test, torque meter telescopic drive shaft
(10) D.C. electric motor, transmission and angular velocity tachometer
(11) Dynamometer carriage
(12) Prepared soil sample containing lead markers

Figure 2.1

on one end of the wheel axle to measure the torque applied by the electric motor via the telescopic drive shaft. The other end of the wheel axle was fitted with a 10 wire slip ring connector to provide electrical connections between rotating instrumentation and the translating recorder and activation input connections attached to the dynamometer carriage. Also affixed to the dynamometer carriage were the power supply for various gauges, the electric drive motor, the transmission between the drive motor and the flexible telescopic drive shaft, and a L.V.D.T. transducer for measuring the wheel sinkage.

The dynamometer carriage itself is supported by hard rubber rollers moving on Z rails which are mounted on the side of the soil bins. The dynamometer carriage is powered via a hydraulically driven double chain mechanism.

Thus with the above facility it is possible to achieve a measure of control over the linear and angular velocity of the test wheel and thereby predetermine the slip rate range.

2.2.3 The X-ray Unit

A 300 kv flash X-ray pulser was used during this study to obtain radiographic plates describing the position of tracer objects within the soil mass at various stages of the transient loading. This information can be interpreted in terms of strains and strain-rate fields to provide input for analysis. The marker positions on the radiographic plates can be interpreted as instantaneous values as the pulse duration is in the order of 100 nanoseconds. The power supply

for the flash X-ray contains a trigger amplifier and selector switch which provides a rate of 2 pulses per second to a maximum of 10 pulses in a sequence. To permit taking several cine flash pictures during the test and to avoid multiple exposure of the plates, moving film cassettes were employed. The mobile cassette holder was attached to a chain drive which was powered by the same unit used for the dynamometer carriage drive. By utilizing suitable gearing the velocity of the cassette drive was twice that of the carriage, thus enabling the mobile cassette holder to be in phase with the wheel at various stages of the test when the flash X-ray unit was fired by the passage of the dynamometer carriage over prepositioned activation switches (see Figure 2.2).

Details of calibrations, corrections, etc., may be found in Yong et al, 1967.

2.2.4 The Recording System

The mechanical test parameters relating to the performance of the driven wheel were monitored by electrical instrumentation and the signal outputs recorded by means of a six channel Ultra Violet Light Oscillograph recorder. The torque and drawbar pull signal outputs were amplified by factor of 50 to 100 prior to recording while the remaining signals were fed directly to the recorder via impendence matching resistors. The latter signals were sinkage measurements obtained from the LVDT, angular velocity of wheel and linear velocity of the carriage as measured by tachometers mounted on the appropriate chain drives.

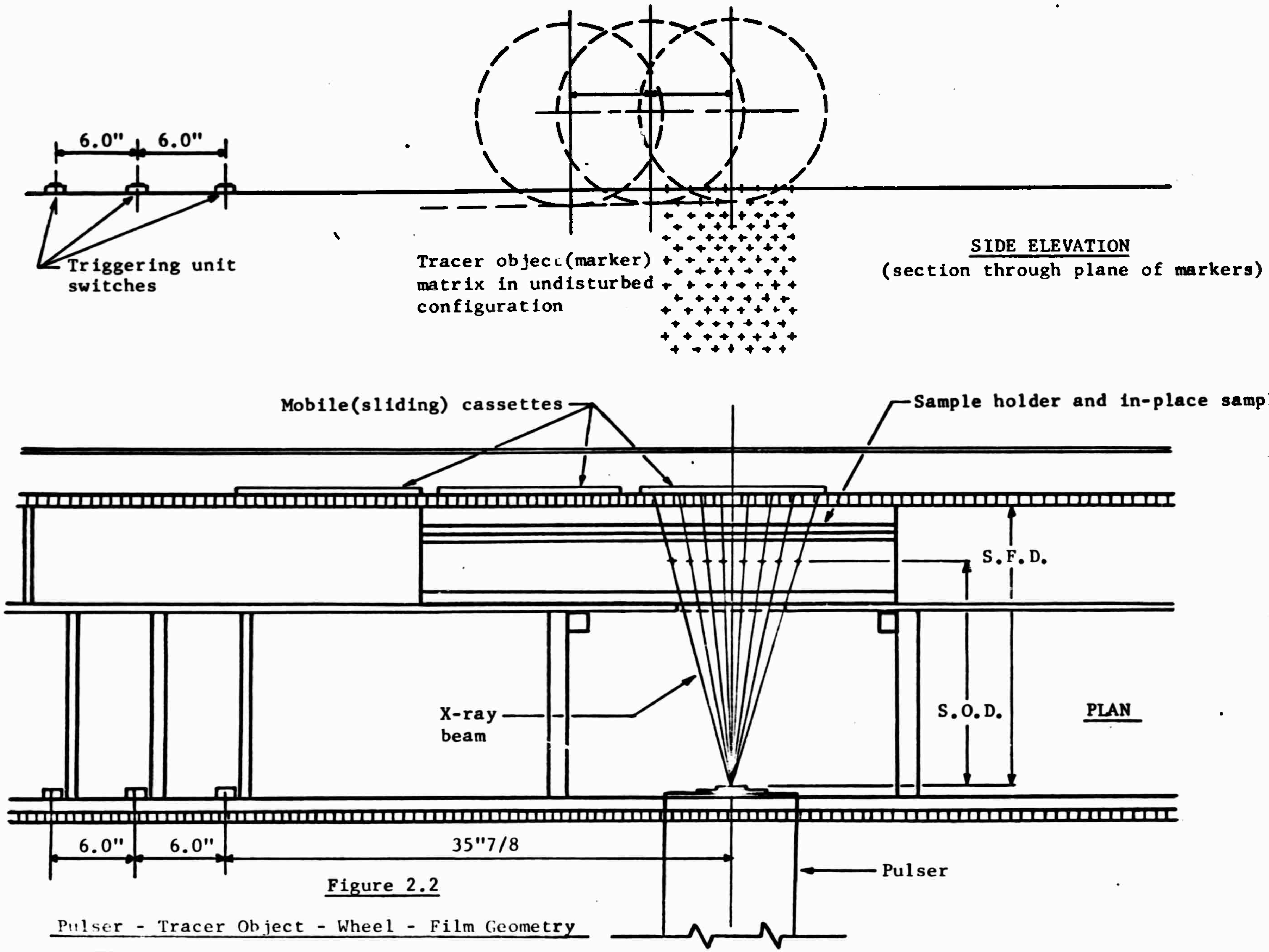


Figure 2.2

Pulser - Tracer Object - Wheel - Film Geometry

2.3 SOIL PREPARATION

The preparation of the soil for each test consisted of two steps: The mixing of the dry powdered clay to a clay-water mix of the desired water content and the placement of the soil in the sample holder or test section.

The clay soil used in these experiments was a commercially refined powdered kaolin with the trade name "English China Clay". A two inch lift of the dry powdered clay was placed in the mixing trough and the required amount of water to produce the desired water content was sprinkled as evenly as possible over the dry clay. This water was allowed to soak in before the next lift was added to the mixing trough. This procedure was followed until the mixing trough contained approximately 400 lbs of wet clay at which time the prepared batch was left to season for a further two to three days. Water content determinations on samples taken at random from batches prepares in the above manner showed that the moisture distribution was still far from uniform. Variations of up to 10% difference in water contents were observed. To improve homogeniety of the mix, the wet clay was thoroughly mixed in the preparation bin by means of mechanical agitation.

The second stage of sample preparation was the placement of the wet soil in the sample holder for subsequent installation in the soil bin. The sample holder was a box consisting of a rigid base, a removable side frame and a removable back plate (see Figure 2.3).

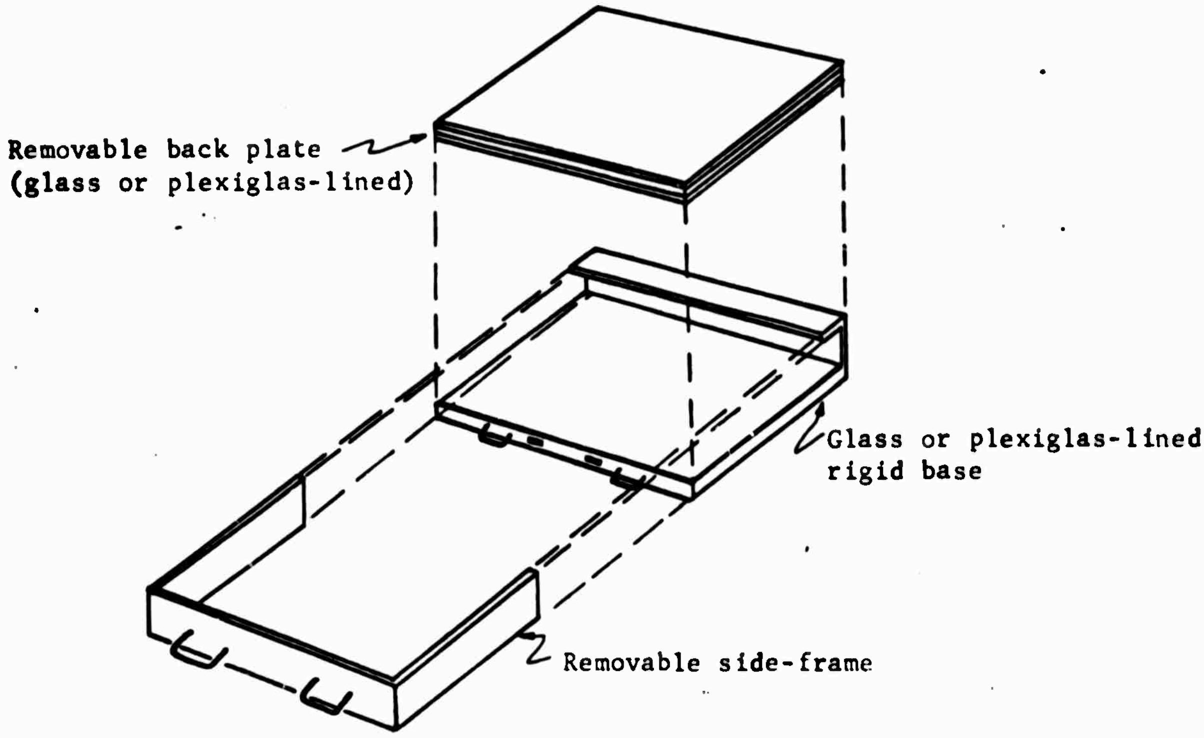


Figure 2.3 Sample Holder

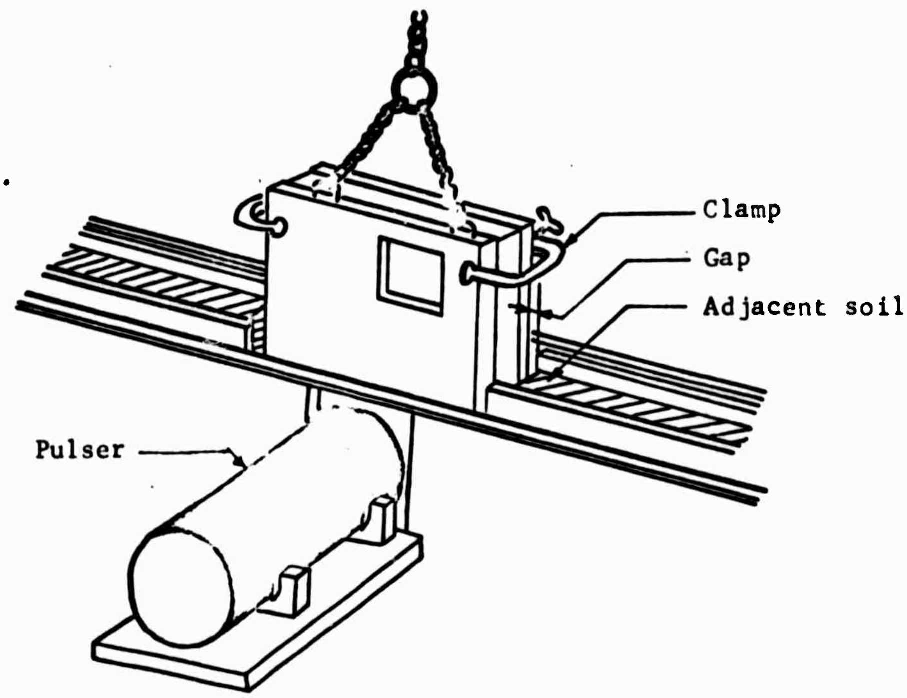


Figure 2.4

Operation of Lowering Prepared Sample(in sample holder) into Test Portion

In the early stages of the program, the top face of the wooden base was covered with a glass plate. This was subsequently changed to a lucite sheet. Prior to the placement of the soil in the holder this base plate was coated with a thin layer of vaseline and then the removable side frame was attached to the base. With the sample holder in the horizontal position, at this stage being similar to a shallow open box, the wet clay was manually placed in the holder in approximately a one inch lift. This lift was then compacted by tamping and hand rolled to provide a sensibly plane surface and to minimize the presence of air voids. The sample was thus built up in successive lifts. When the sample thickness was one half of the depth of the holder, the tracer objects or lead markers were installed as follows.

A pre-punched template with holes at the required grid node spacing was placed on the prepared surface. One edge of the template was positioned firmly against the removable side frame and the template was moved along this guiding edge until its centerline was in alignment with a reference mark on the removable frame. The template was then gently pressed against the prepared soil surface and then removed, leaving slightly raised marks at the required marker locations. The markers were then inserted into the desired locations by means of tweezers. The filling and tamping of the soil sample was then continued until it was slightly thicker than the sample box. A wire saw was used to trim off the excess soil to a plane

surface flush with the edges of the removable side frame. The removable back plate which was coated with vaseline was then put in place and the sample holder firmly clamped together. A mobile ceiling crane was employed to lift the sample holder and lower it into the test position which was located directly in front of the X-ray pulser (see Figure 2.4).

The side frames of the sample holder were then removed and the gaps between the edges of the test section soil and the soil in the test bin were filled with similar soil from the test batch. This soil was tamped in place carefully with due caution to avoid disturbance of the test section. The surface of the prepared test section was smoothed with a wire saw and scraper and the surface markers put in place.

Once the sample holder was installed and the soil preparation completed, an initial X-ray picture was taken to check the alignment of the markers. As will be subsequently discussed, the compaction of the soil between the holder and that of the bin, together with the action of moving the test section from the horizontal to the vertical attitude, at which time the self weight of the material becomes of greater importance, resulted in some distortion of the marker grid. In the instances when it was felt that the distortion was excessive, the sample holder was removed and the entire placement procedure repeated.

In some instances the installed test section was preloaded for several days by surface loading in an attempt to reduce the void ratio of the prepared soil.

The clay soil in the bin which was adjacent to the test section was kept in usable condition by the use of plastic covering and occasional sprinkling of water to maintain a high humidity and reduce desiccation. However, this material was periodically replaced with soil from a new batch.

2.4 TEST DESCRIPTION

Once the sample holder had been installed, and the position of the grid markers checked, the following steps were necessary during the performance of the test. To permit calculations employing data from the X-ray plates indicating marker positions, the following distance measurements were required: source (base of X-ray tube) to object (marker plane) distance - "S.O.D.", source to film (face of cassette) distance "S.F.D.", the difference in elevation between the test section surface and the reference position of the wheel from which point the recorder traces are zeroed, and the depth of the optical center below the soil surface.

The X-ray film cassettes were then installed on the mobile cassette drive and the X-ray unit brought to standby. The dynamometer carriage was advanced until the test wheel was in the desired initial reference position, this being an aluminum plate approximately flush

with the prepared soil surface. The recording system was brought to a state of readiness, the electrical circuitry actuated and the reference zero traces recorded and identified.

The flow control valves of the hydraulic unit powering the chain drive for the dynamometer carriage were set to produce the desired carriage velocity. Similarly the rheostat control for the electric wheel drive was positioned so as to produce the required angular velocity or slip.

All systems were then activated and the test conducted. At this time the exposed X-ray plates were removed and developed. A final X-ray exposure having been taken at the end of the test. In this way the location of the marker objects before, during and after the test was established.

2.5 EXPERIMENTAL DIFFICULTIES

With the sample preparation technique that was employed, it was virtually impossible to obtain homogeneous saturated specimens. The degree of saturation obtained was variable and ranged between 0.85 and 0.95. Water content determinations often showed up to 5% variations within several inches. The preparation techniques employed during the program were adopted as an expedient until more refined preparation techniques are evolved to handle the problem of producing a uniform homogeneous sample with an embedded marker grid system. In-situ consolidation of a sample from a de-aired clay-water slurry is a

possible alternative to achieve full saturation but homogeneity is not ensured, the marker placement becomes more difficult and the whole process is so time consuming that it was not considered to be feasible for this short term contract period. Thus some of the test data obtained are more than likely influenced by the variations in the soil in the test section.

Another difficulty that was encountered and which caused several delays in the testing program was the distortion of the marker grid due to compaction of soil adjacent to the test section and the actual process of installing the sample holder in the soil bin. During the process of compacting soil in the gap between the soil in the test section and that in the bin, one could never be certain if the gap was totally filled. Excessive compaction of the soil placed in the gap, while insuring minimum void spaces, inevitably resulted in a distortion of the prepared sample and hence the marker grid. This effect was physically manifested by a surface heave of the test section. As the filling of this gap neared the surface it was possible for the effect to be reversed in that the surface was dragged down by the compaction of the "in-gap" material. On the other hand under-compaction of the gap material would result in large void spaces in the gap into which the prepared soil could flow either during preloading or during the actual test itself.

Other sources of the distortion of the marker grid system were the building up of the second half of the sample after the

markers were in place and the physical act of lifting the horizontally prepared sample into the vertical position, transporting it to the test bin and installing it in place.

Whatever the cause of the distortion of the marker grid, if the initial X-ray plate indicated that it was excessive the sample was removed and the entire preparation procedure was repeated. Whenever this replacement was necessary, it resulted in an increase of several days in the test preparation period.

As the test facility was not located in a humidity controlled room, it was difficult to predict moisture content changes that would occur between the time of sample preparation and actual testing. This factor was of more significance in tests with preloading due to the longer interim and particularly during the summer months. During humid weather, the moisture evaporation was very slight but in the hot dry periods it resulted in a moisture loss equivalent to a 3 to 4 percent decrease in water content. In several instances this loss was condidered excessive and the sample preparation procedure had to be repeated.

2.6 CONTROL OF TEST PARAMETERS

As was stated earlier the linear velocity and the angular velocity of the driven wheel were powered from separate sources. The linear velocity of the dynamometer carriage was regulated by hydraulic flow control valves. Unfortunately the carriage velocity resulting

from any particular valve setting was influenced by the resistance to motion encountered. Thus a particular valve setting does not produce a unique velocity but is influenced by the state of the soil and the driving torque applied to the rolling wheel. Theoretically the torque applied to the driven wheel by an indepe~dent electrical system should be constant for a preselected power input, however inhomogeneities in the soil, together with the variable carriage velocity resulted in variations in angular velocity, applied torque, and the slip rate. Thus it was not possible to produce a control chart that would allow preselection of settings to provide a required torque, angular velocity, or slip rate.

The sinkage of the driven wheel was not a controlled parameter and hence could not be prescribed. The sinkage was merely measured during the tests. For the reasons stated above it was not possible to precisely specify the test parameters in a fashion that would be desirable in a model study.

2.7 RESULTS OF DRIVEN WHEEL TESTS

The results of the tests conducted can be subdivided into five groups of raw data as follows:

1. geometrical parameters, S.O.D., F.O.D., etc.;
2. X-ray plates showing enlarged images of the buried grid markers for different wheel positions, i.e., various stages of transient loading;
3. U.V. recorder traces which indicate the magnitude of the test parameters monitored;

4. soil data consisting of water content and shear strength measurements;

5. data relating to fabric distortion and evaluation.

Item number 5. above is contained in a separate report. The U.V. recorder traces were interpreted at McGill and provided the following test parameter measurements: torque (in.-lbs), drawbar pull (lbs), carriage velocity (in./sec.), angular velocity (rev./sec.) and sinkage (ins.). The geometrical test parameters, the developed X-ray plates, the calculated test parameters and data from soil tests were forwarded to C.A.L. upon the completion of each test.

The data obtained from soil tests are presented in tabular form in Table 2.1. The wheel data, test data and geometrical parameters for the tests conducted are presented in Table 2.2.

The results of the conventional and true triaxial tests conducted are presented in the form of stress-strain curves (see Figures 2.5 to 2.10). Since the X-ray plates were forwarded to C.A.L. as per their request, no data describing the marker positions at various stages of the test are included in this report.

TABLE 2.1

SOIL DATA

Test No.	Average Water Content (%)	Sample Fabric Study	Soil Data Notes
Cal 1	50.4	/	
Cal 2R	49.03		
Cal 3	45.6	/	One triaxial test (figure)
Cal 4	50.6	/	One "true" and one standard triaxial test (figure)
Cal 5	49.1		From this test on a new batch of clay was used. Compaction was increased.
Cal 6			Second run on same soil as for Cal 5.
Cal 7	49.1		Saturation = 0.93
Cal 8	47.2	/	Saturation = 0.885 Preloaded for approximately 2 weeks. Depth (in) | Water Content (%) 2 - 3 | 45.0 5 - 6 | 47.5 9 - 10 | 48.2
Cal 9,10, 11	49.0		Saturation = 0.89 These tests were done on the same soil sample.
Cal 12,13, 14,15			Depth (in) | Water content(%) before preloading | Water content(%) after 8 days of preloading 0 - 1 | 52.7 | 46.3 2 - 3 | 50.9 | 46.2 4 - 5 | 54.4 | 41.4 6 - 7 | 49.8 | 41.6 These wheel tests were done on the same soil sample.

TABLE 2.1 Continued

Test No.	Average Water Content (%)	Sample for Fabric Study	Soil Data Notes
Cal 16,17		/	Average moisture content before preloading = 58 % After 3-days preloading : Depth (in) | Water Content (%) 0 - 1 | 52.7 2 - 3 | 53.1 4 - 5 | 54.4 6 - 7 | 54.8 9 - 10 | 52.0 Shear strength by laboratory vane test (4 tests at 3 in. depth) : 1.53 to 1.90 psi, average = 1.74 psi. These wheel tests were done on the same soil sample.
Cal 18		/	Depth (in) | Water content(%) after test 0 - 1 | 57.7 2 - 3 | 54.6 4 - 5 | 54.1 6 - 7 | 53.1 9 - 10 | 53.4 Shear strength by laboratory vane test (5 tests at 4.0 in. depth) : 1.11 to 1.39 psi., Average = 1.26 psi.
Cal 19		/	Depth (in) | Water content(%) after test 0 - 1 | 53.2 2 - 3 | 53.8 4 - 5 | 55.1 6 - 7 | 56.3 9 - 10 | 56.8

TABLE 2.2

TEST PARAMETERS

Test No.	Wheel Data			Test Data					X-Ray Data		
	Radius (inches)	Width (inches)	Total Weight (lbs)	Angular Velocity (revs/sec)	Carrage Velocity (in/sec)	Drawbar Pull (lbs)	Sinkage (inches)	Torque (in-lbs)	S.O.D. (inches)	S.F.D. (inches)	Depth of Optical Center (inches)
Cal 1	6.75	3.75	34.0	0.16	5.45	14.28	0.43	140.57	16.5	18.5	
Cal 2R	6.75	3.75	54.0	0.171	4.66	17.46	0.44	154.4	14.75	18.5	2.1
Cal 3	6.75	3.75	74.0	0.117	2.23	13.2	0.83	298.0	14.8	18.8	1.95
Cal 4	6.75	3.75	74.0	0.117	3.00	2.2	0.71	249.0	14.0	18.7	1.9
Cal 5	6.75	3.75	74.0	0.198	4.35	9.17	0.82	151.0	14.0	18.7	2.0
Cal 6	6.75	3.75	74.0	0.157	4.12	7.6	0.79	162.0	14.0	18.7	1.87
Cal 7	6.75	3.75	74.0	0.107	3.22	12.4	0.75	140.0	14.0	18.7	2.00
Cal 8	6.75	3.75	74.0	0.101	4.32	0.7	0.35	313.0	14.5	19.3	1.25
Cal 9	6.75	3.75	74.0	0.076	3.12	-3.6	0.6	113.0	14.5	18.0	1.4
Cal 10	6.75	3.75	74.0	0.095	3.25	6.3	0.6	170.0	14.0	18.9	1.3
Cal 11	6.75	3.75	74.0	0.231	3.36	11.3	0.5	251.0	14.0	18.9	1.2
Cal 12	4.50	2.50	26.0	0.065	2.06	5.3	0.00	108.0	20.7	26.5	2.7

TABLE 2.2 Continued

Test No.	Wheel Data			Test Data					X-Ray Data		
	Radius (inches)	Width (inches)	Total Weight (lbs)	Angular Velocity (revs/sec)	Carrage Velocity (in/sec)	Drawbar Pull (lbs)	Sinkage (inches)	Torque (in-lbs)	S.O.D. (inches)	S.F.D. (inches)	Depth of Optical Center (inches)
Cal 13	4.50	2.50	26.0	0.082	2.40	7.40	0.00	169	20.7	26.5	2.7
Cal 14	4.50	2.50	26.0	0.110	2.40	14.0	0.1	190	20.7	26.5	2.7
Cal 15	4.50	2.50	26.0	0.203	2.22	16.0	0.00	186	20.7	26.5	2.7
Cal 16	4.50	2.50	34.0	0.106	2.35	2.8	0.17	48.0	19.5	25.3	2.4
Cal 17	4.50	2.50	34.0	0.107	2.08	11.7	0.15	68.0	19.5	25.3	2.4
Cal 18	4.50	2.50	34.0	0.146	2.32	-2.6	1.20	48.0	19.5	24.0	4.1
Cal 19	4.50	2.50	34.0	0.096	2.19	8.3	0.5	56.5	19.5	24.0	3.4

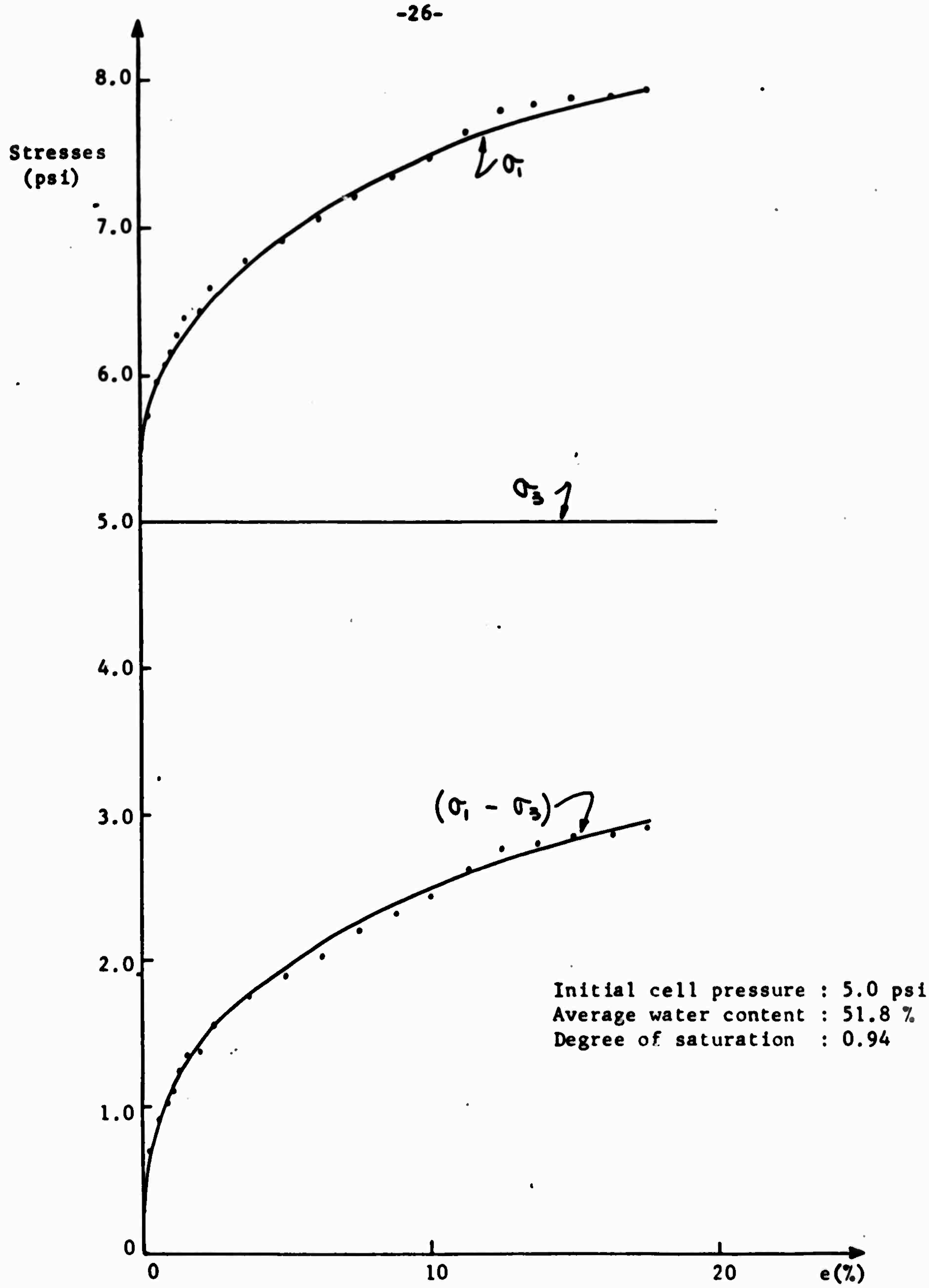
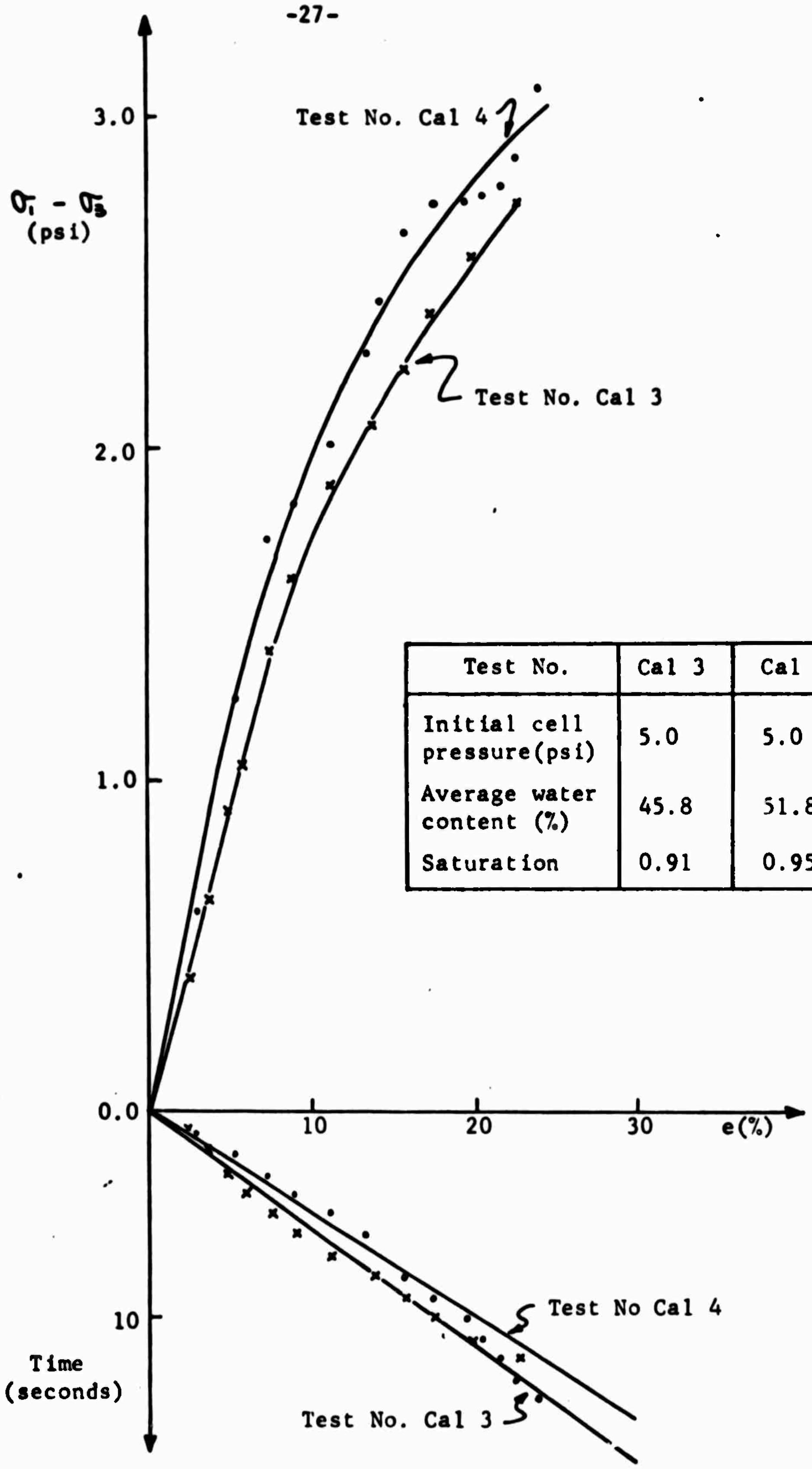


Figure 2.5

"True" Triaxial Test Results, Test No. Cal 4

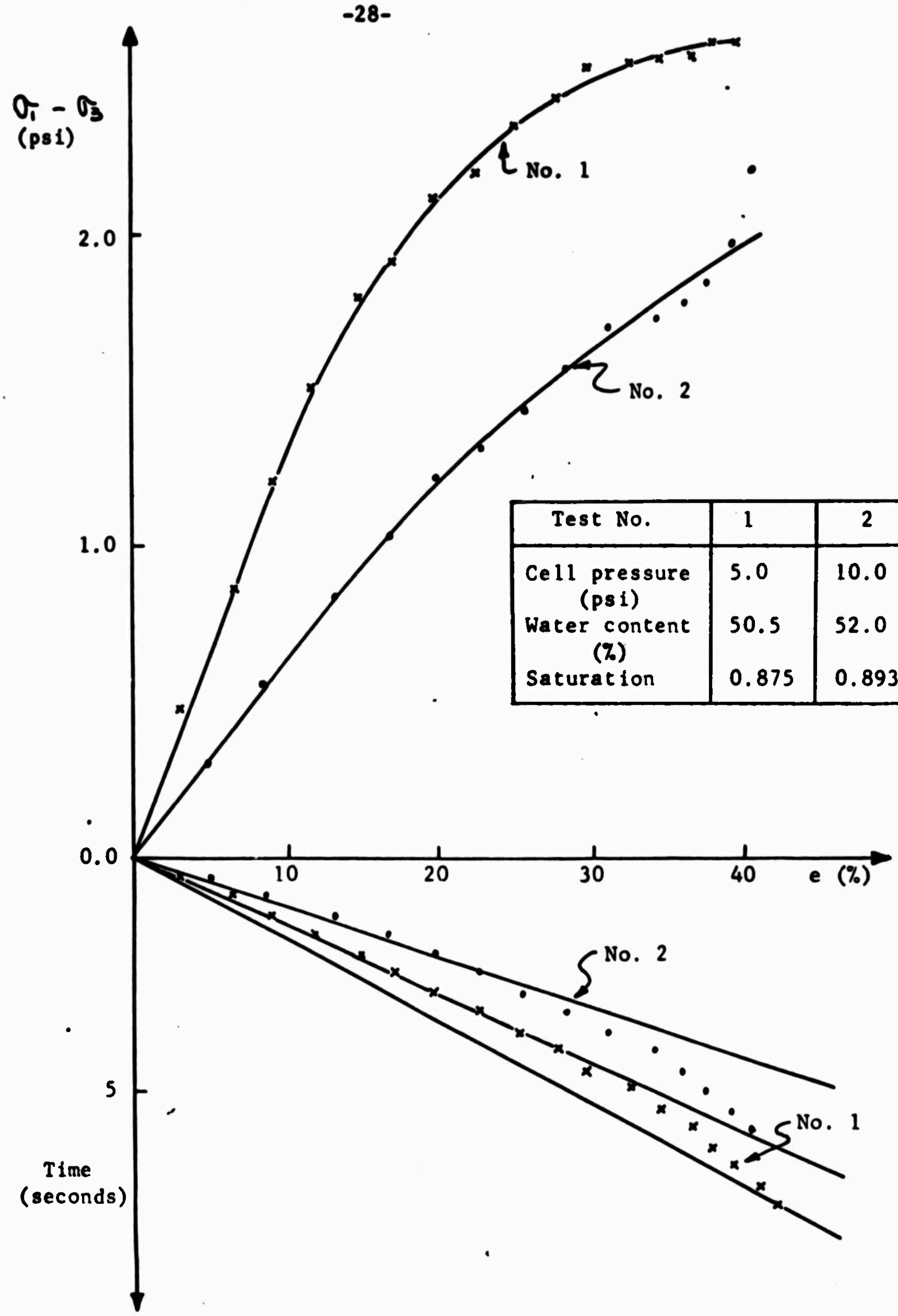


Test No.	Cal 3	Cal 4
Initial cell pressure(psi)	5.0	5.0
Average water content (%)	45.8	51.8
Saturation	0.91	0.95

Figure 2.6

Triaxial Test Results (Standard Unconsolidated, Undrained Tests)

Test Nos Cal 3 and Cal 4

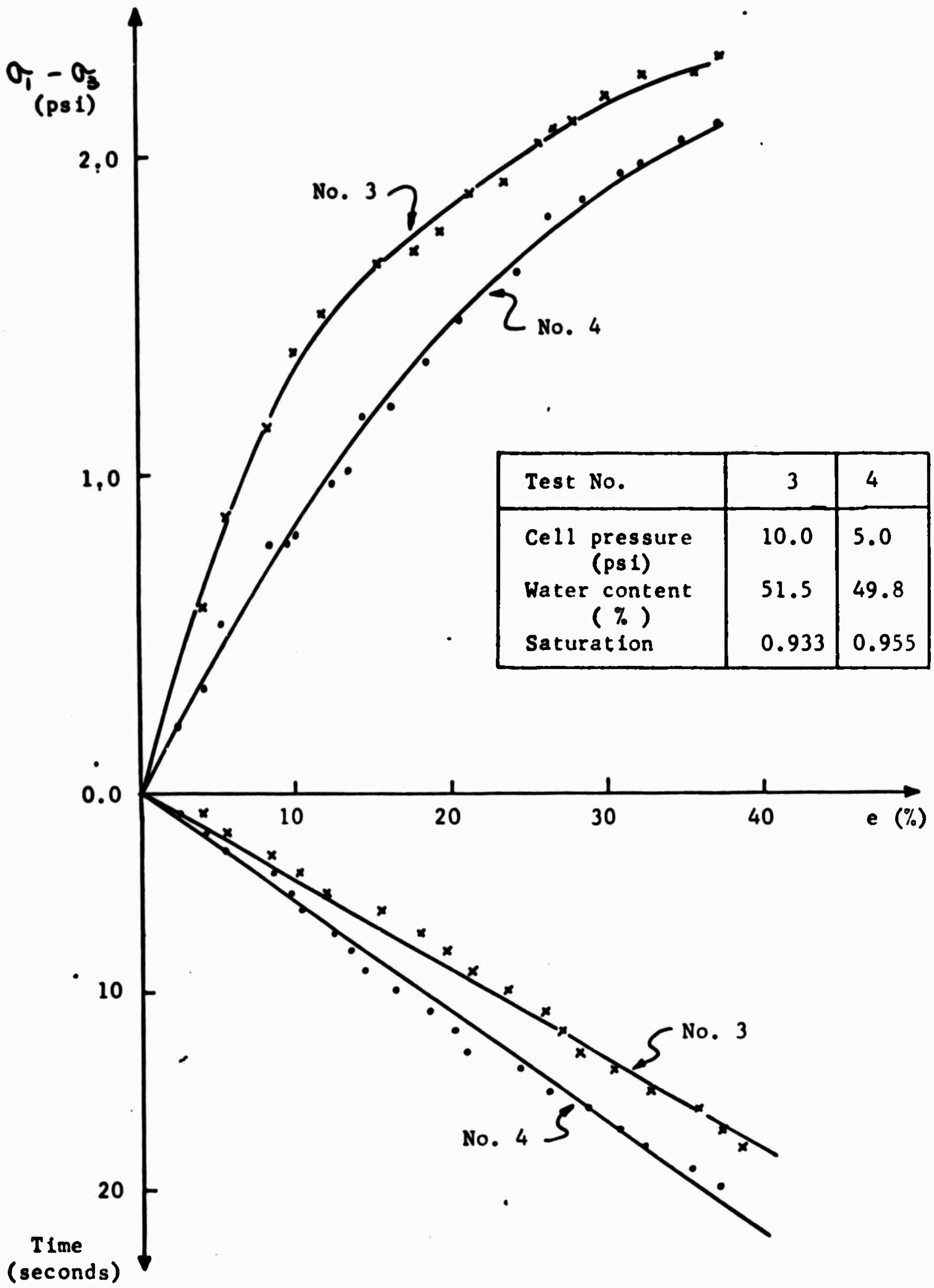


Test No.	1	2
Cell pressure (psi)	5.0	10.0
Water content (%)	50.5	52.0
Saturation	0.875	0.893

Figure 2.7

Triaxial Test Results (Standard Unconsolidated, Undrained Tests)

Test Nos Cal 1 and Cal 2



Test No.	3	4
Cell pressure (psi)	10.0	5.0
Water content (%)	51.5	49.8
Saturation	0.933	0.955

Figure 2.8

Triaxial Test Results (Standard Unconsolidated, Undrained Tests)

Test Nos Cal 3 and Cal 4

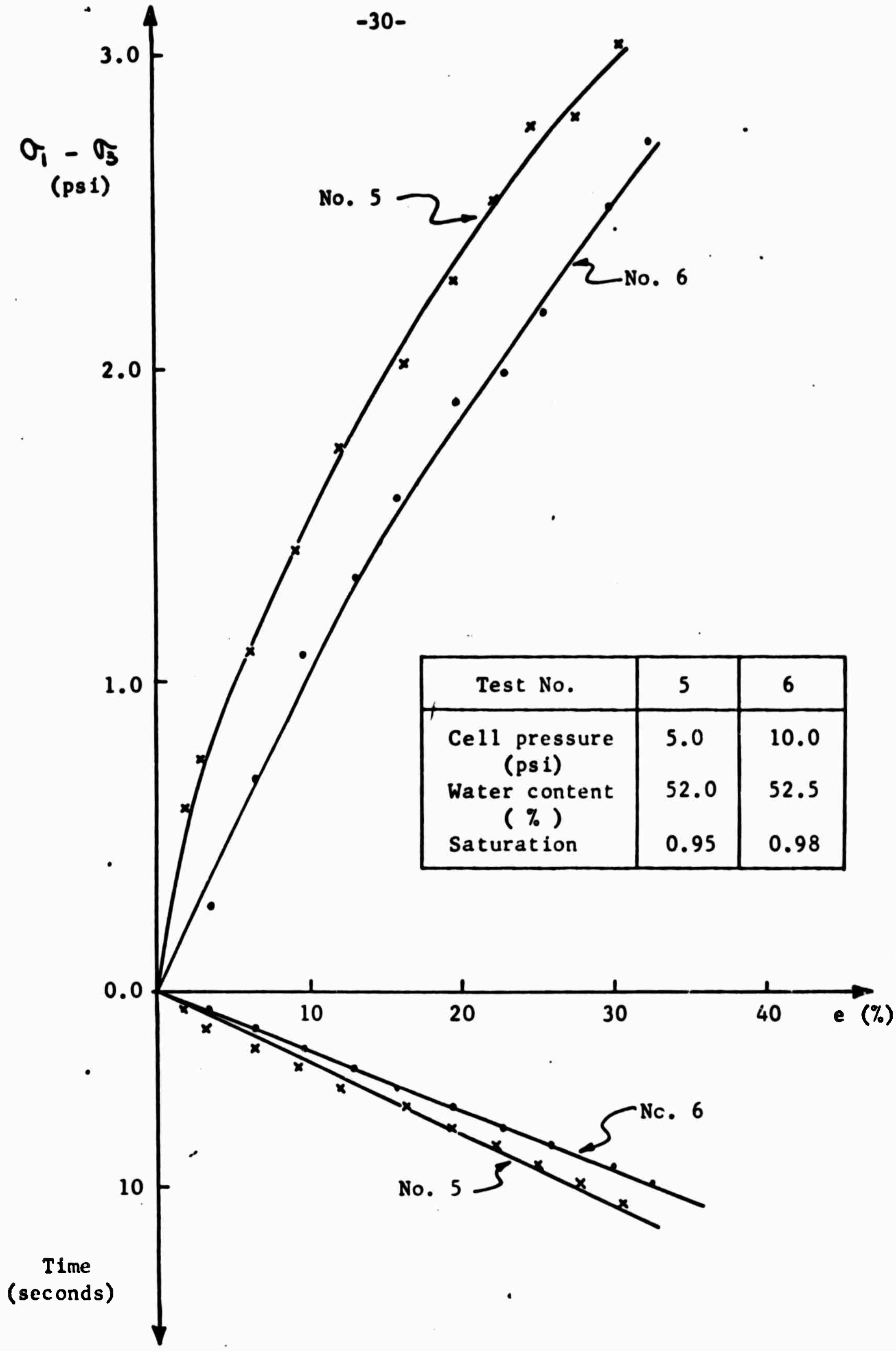


Figure 2.9

Triaxial Test Results (Standard Unconsolidated, Undrained Tests)

Test Nos Cal 5 and Cal 6

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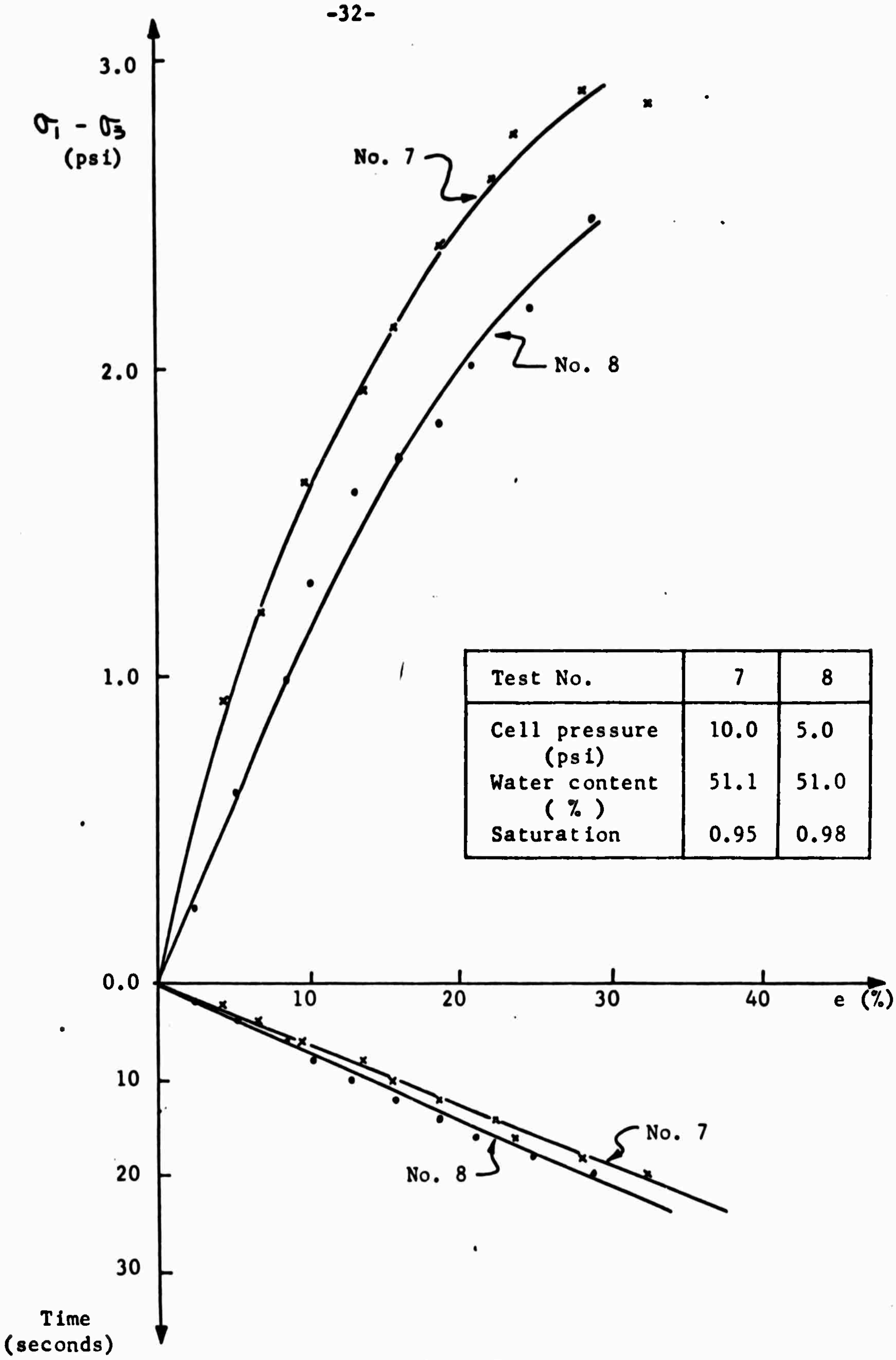

Test No.	7	8
Cell pressure (psi)	10.0	5.0
Water content (%)	51.1	51.0
Saturation	0.95	0.98

Figure 2.10

Triaxial Test Results (Standard Unconsolidated, Undrained Tests)

Test Nos Cal 7 and Cal 8

SECTION 3 - TOWED WHEEL TESTS

3.1 INTRODUCTION

During the term of the present contract, an independent study was conducted to examine a specific case in the overall wheel-soil interaction problem. This study consisted of a series of ten towed wheel tests conducted with the experimental facility described in Section 2. The towed tests were achieved by disconnecting the electrically powered independent wheel drive. The sample preparation techniques, X-ray plates obtained, and mechanical tests parameters measured, with the exceptions of driving torque and angular velocity of the wheel, were as previously described. In this test series an electrical circuit that was momentarily completed for each half revolution of the wheel was devised. The signals from this circuit were recorded on the ultra-violet recorder system and the time interval between pulses was used to calculate an average angular velocity.

Of the ten tests conducted in this series, only the results from six tests are included in this report. The results from the remaining tests have been discarded due to incomplete data resulting primarily from malfunctions of the X-ray system.

Although these tests do not form a part of the contract study, they are considered relevant to the problem under study and have thus been included to provide a broader base for analytic studies.

3.2 DATA REDUCTION AND RESULTS

From the X-ray plates obtained for each test, the observed marker locations were used to calculate the strain-rate fields occurring in the soil due to the passage of the wheel. To achieve this end a technique similar to that developed earlier at McGill (McGill Soil Mechanics Series No. 25) was employed. The components of the strain-rate fields calculated in this manner are shown in Tables 3.1 to 3.6. To provide some physical insight into the nature of the strain rate field with the soil for a towed wheel test, the results of Test No. 6 have been plotted in Figures 3.1 to 3.3. The pertinent test parameters and soil data for the towed wheel investigation are presented in Table 3.7.

If desired, the above strain-rate fields can be used to examine the energy dissipation in the soil by making use of the method of analysis described in McGill Soil Mechanics Series No. 25.

TABLE 3-1

STRAIN RATES (SECONDS^{-1}). TEST NO. W3

Depth below original soil surface (inches)

Horizontal distance from wheel axis (inches). Direction of wheel travel →

	1.2	2.2	3.2	4.2	5.2	6.2
+6	-.024 +.053 -.110	-.010 +.014 -.144	-.012 +.005 -.107	-.014 +.006 -.077	-.008 +.004 -.034	+.008 -.011 -.011
+5	+.008 -.010 -.097	+.018 -.026 -.096	+.010 -.030 -.067	+.004 -.022 -.050	+.004 -.010 -.028	+.010 -.015 -.010
+4	+.030 -.049 -.078	+.036 -.051 -.050	+.025 -.050 -.029	+.017 -.036 -.020	+.012 -.017 -.017	+.011 -.017 -.004
+3	+.043 -.069 -.053	+.045 -.063 -.009	+.034 -.057 +.006	+.024 -.040 +.006	+.017 -.019 -.003	+.010 -.018 +.003
+2	+.047 -.072 -.026	+.045 -.064 +.027	+.036 -.053 +.037	+.025 -.035 +.029	+.018 -.017 +.013	+.007 -.018 +.011
+1	+.043 -.062 +.003	+.038 -.056 +.055	+.032 -.042 +.060	+.021 -.026 +.047	+.015 -.013 +.027	+.004 -.015 +.019
0	+.033 -.044 +.031	+.026 -.039 +.073	+.024 -.026 +.075	+.015 -.013 +.057	+.011 -.008 +.038	.000 -.012 +.025
-1	+.019 -.020 +.053	+.010 -.018 +.081	+.012 -.007 +.081	+.005 -.001 +.061	+.005 -.003 +.045	-.003 -.007 +.029
-2	+.001 +.004 +.067	-.008 +.005 +.077	-.001 +.011 +.076	-.004 +.011 +.056	-.002 +.002 +.045	-.006 -.001 +.030
-3	-.016 +.025 +.070	-.024 +.026 +.062	-.014 +.027 +.060	-.013 +.019 +.043	-.008 +.006 +.038	-.007 +.006 +.027
-4	-.031 +.041 +.055	-.037 +.043 +.034	-.025 +.037 +.033	-.018 +.022 +.023	-.011 +.007 +.025	-.005 +.011 +.020
-5	-.039 +.047 +.019	-.041 +.049 -.006	-.031 +.038 -.005	-.018 +.020 -.003	-.012 +.007 +.005	.000 +.015 +.007
-6	-.039 +.041 -.045	-.033 +.042 -.056	-.030 +.029 -.053	-.008 +.013 -.032	-.007 +.005 -.020	+.011 +.015 -.010

NOTE : The strain rate components are in the order $\dot{\epsilon}_x$
$\dot{\epsilon}_y$
(compression is negative) $\dot{\gamma}_{xy}$

TABLE 3-2

STRAIN RATES (SECONDS^{-1}). TEST NO. W4

Depth below original soil surface (inches)

Horizontal distance from wheel axis (inches). Direction of wheel travel ⟶

	0.7	1.7	2.7	3.7	4.7	5.7
+6	-.007	+.051	+.049	+.034	+.040	+.028
	-.681	-.093	+.062	-.035	-.173	-.116
	-.317	-.275	-.214	-.158	-.115	-.013
+5	+.032	+.065	+.054	+.036	+.023	+.020
	-.487	-.114	-.017	-.085	-.177	-.117
	-.155	-.122	-.091	-.058	-.042	+.002
+4	+.056	+.068	+.052	+.034	+.010	+.013
	-.260	-.101	-.065	-.106	-.152	-.099
	-.028	-.003	+.006	+.021	+.017	+.013
+3	+.065	+.062	+.044	+.028	-.001	+.006
	-.038	-.069	-.086	-.103	-.109	-.070
	+.059	+.080	+.075	+.077	+.058	+.018
+2	+.062	+.049	+.032	+.019	-.008	.000
	+.143	-.030	-.086	-.084	-.060	-.038
	+.106	+.128	+.118	+.110	+.082	+.019
+1	+.048	+.029	+.016	+.008	-.012	-.005
	+.260	+.011	-.068	-.055	-.015	-.008
	+.112	+.143	+.134	+.119	+.087	+.017
0	+.026	+.005	-.002	-.004	-.013	-.010
	+.296	+.042	-.039	-.022	+.020	+.013
	+.083	+.129	+.127	+.108	+.077	+.011
-1	+.001	-.019	-.019	-.015	-.011	-.012
	+.252	+.057	-.004	+.009	+.039	+.023
	+.030	+.092	+.101	+.081	+.054	+.005
-2	-.024	-.040	-.032	-.023	-.006	-.012
	+.142	+.057	+.030	+.033	+.041	+.021
	-.034	+.041	+.061	+.043	+.022	-.002
-3	-.044	-.055	-.039	-.026	.000	-.010
	+.001	+.044	+.055	+.046	+.028	+.010
	-.090	-.013	+.015	.000	-.012	-.007
-4	-.052	-.058	-.037	-.022	+.008	-.005
	-.115	+.024	+.064	+.045	+.007	-.005
	-.114	-.058	-.031	-.037	-.039	-.008
-5	-.041	-.044	-.020	-.007	+.017	+.005
	-.125	+.010	+.048	+.027	-.011	-.017
	-.078	-.079	-.065	-.057	-.049	-.002
-6	-.005	-.008	+.015	+.021	+.025	+.019
	+.079	+.019	-.003	-.007	-.007	-.011
	+.055	-.057	-.075	-.047	-.029	+.014

NOTE :The strain rate components are in the order $\dot{\epsilon}_x$
$\dot{\epsilon}_y$
(compression is negative) $\dot{\gamma}_{xy}$

TABLE 3-3

STRAIN RATES (SECONDS^{-1}). TEST NO. W5

Depth below original soil surface (inches)

Horizontal distance from wheel axis (inches). Direction of wheel travel ↑

	0.7	1.7	2.7	3.7	4.7	5.7
+6	-.060 -.416 -.093	-.054 -.045 -.123	-.019 +.064 -.101	-.033 +.024 -.064	.000 -.049 -.043	-.002 -.037 -.021
+5	+.010 -.337 -.007	+.015 -.070 -.085	+.015 +.013 -.095	+.002 -.008 -.069	+.010 -.050 -.040	-.001 -.032 -.016
+4	+.056 -.206 +.044	+.061 -.074 -.044	+.038 -.029 -.069	+.026 -.031 -.057	+.016 -.042 -.030	+.001 -.023 -.011
+3	+.081 -.050 +.068	+.085 -.063 -.004	+.050 -.060 -.033	+.040 -.046 -.032	+.019 -.028 -.015	+.001 -.014 -.005
+2	+.086 +.103 +.071	+.088 -.041 +.031	+.052 -.078 +.007	+.045 -.052 -.002	+.019 -.012 +.001	+.001 -.004 +.001
+1	+.074 +.229 +.061	+.073 -.014 +.057	+.045 -.082 +.044	+.041 -.050 +.028	+.016 +.005 +.018	+.001 +.005 +.007
0	+.049 +.308 +.042	+.046 +.014 +.072	+.032 -.072 +.071	+.030 -.040 +.053	+.011 +.019 +.032	+.001 +.011 +.013
-1	+.015 +.327 +.021	+.011 +.038 +.074	+.014 -.049 +.086	+.015 -.023 +.069	+.004 +.028 +.042	.000 +.014 +.018
-2	-.020 +.279 +.002	-.026 +.055 +.062	-.006 -.016 +.083	-.003 -.002 +.073	-.003 +.030 +.047	-.001 +.013 +.022
-3	-.050 +.164 -.012	-.057 +.061 +.039	-.025 +.023 +.062	-.020 +.021 +.063	-.010 +.025 +.045	-.001 +.007 +.024
-4	-.068 -.005 -.018	-.074 +.054 +.005	-.038 +.063 +.025	-.033 +.042 +.037	-.015 +.012 +.037	-.001 -.002 +.024
-5	-.064 -.208 -.016	-.068 +.032 -.034	-.041 +.096 -.026	-.038 +.057 -.002	-.017 -.007 +.020	-.001 -.015 +.021
-6	-.028 -.409 -.005	-.027 -.004 -.071	-.030 +.113 -.083	-.031 +.062 -.051	-.014 -.032 -.003	+.001 -.031 +.014

NOTE : The strain rate components are in the order $\dot{\epsilon}_x$, $\dot{\epsilon}_y$, $\dot{\gamma}_{xy}$

(compression is negative)

TABLE 3-4

STRAIN RATES (SECONDS^{-1}). TEST NO. W6

Depth below original soil surface (inches)

Horizontal distance from wheel axis (inches). Direction of wheel travel →

	1.2	2.2	3.2	4.2	5.2	6.2
+6	+.009	+.063	+.038	+.055	+.006	+.001
	+.041	-.049	-.062	-.032	-.006	-.046
	-.193	-.246	-.189	-.047	-.044	-.064
+5	+.057	+.083	+.062	+.054	+.018	+.007
	-.089	-.094	-.092	-.072	-.036	-.006
	-.129	-.142	-.104	-.043	-.025	-.031
+4	+.086	+.089	+.073	+.048	+.025	+.012
	-.150	-.112	-.100	-.084	-.048	+.012
	-.074	-.049	-.024	-.026	-.003	-.002
+3	+.096	+.083	+.072	+.040	+.028	+.014
	-.159	-.107	-.090	-.077	-.045	+.014
	-.029	+.029	+.046	.000	+.018	+.021
+2	+.088	+.067	+.061	+.028	+.027	+.014
	-.130	-.086	-.068	-.055	-.034	+.008
	+.005	+.087	+.100	+.027	+.036	+.037
+1	+.067	+.042	+.042	+.015	+.022	+.012
	-.080	-.054	-.038	-.027	-.018	-.003
	+.030	+.122	+.133	+.052	+.048	+.046
0	+.036	+.013	+.017	+.001	+.014	+.008
	-.022	-.017	-.005	+.002	-.001	-.013
	+.045	+.134	+.143	+.069	+.052	+.048
-1	-.001	-.018	-.011	-.013	+.004	+.004
	+.032	+.020	+.025	+.027	+.013	-.019
	+.050	+.122	+.129	+.075	+.049	+.044
-2	-.038	-.046	-.037	-.024	-.006	-.002
	+.073	+.051	+.050	+.045	+.023	-.020
	+.045	+.089	+.094	+.070	+.038	+.035
-3	-.067	-.065	-.057	-.032	-.016	-.008
	+.093	+.071	+.064	+.052	+.027	-.015
	+.030	+.041	+.044	+.051	+.021	+.023
-4	-.082	-.069	-.066	-.034	-.023	-.013
	+.091	+.077	+.065	+.049	+.026	-.007
	+.004	-.015	-.014	+.023	+.002	+.010
-5	-.074	-.052	-.057	-.028	-.026	-.016
	+.067	+.063	+.051	+.037	+.021	+.001
	-.034	-.069	-.066	-.011	-.016	.000
-6	-.033	-.006	-.025	-.011	-.024	-.018
	+.026	+.026	+.020	+.018	+.015	+.001
	-.087	-.106	-.097	-.043	-.025	-.004

NOTE : The strain rate components are in the order $\dot{\epsilon}_x$, $\dot{\epsilon}_y$, $\dot{\gamma}_{xy}$

(compression is negative)

TABLE 3-5

STRAIN RATES (SECONDS^{-1}). TEST NO. W7

Depth below original soil surface (inches)

Horizontal distance from wheel axis (inches). Direction of wheel travel ⟶

	0.7	1.7	2.7	3.7	4.7	5.7
	-.064	-.040	-.016	-.006	-.034	-.002
+6	+.175	+.040	-.037	-.071	-.075	-.056
	-.500	-.479	-.429	-.377	-.213	-.116
	+.076	+.109	+.113	+.084	+.032	+.024
+5	-.102	-.087	-.113	-.147	-.152	-.090
	-.260	-.261	-.240	-.165	-.110	-.061
	+.165	+.199	+.189	+.138	+.075	+.041
+4	-.227	-.166	-.164	-.177	-.166	-.093
	-.121	-.084	-.065	+.012	-.015	-.008
	+.204	+.233	+.217	+.159	+.095	+.049
+3	-.240	-.201	-.185	-.170	-.137	-.074
	-.052	+.050	+.084	+.142	+.065	+.037
	+.200	+.217	+.200	+.150	+.096	+.047
+2	-.180	-.196	-.179	-.136	-.084	-.046
	-.025	+.141	+.194	+.219	+.124	+.073
	+.160	+.161	+.147	+.116	+.079	+.038
+1	-.083	-.157	-.146	-.086	-.026	-.017
	-.016	+.190	+.257	+.241	+.158	+.096
	+.094	+.076	+.069	+.063	+.049	+.023
0	+.019	-.093	-.090	-.029	+.025	+.006
	-.007	+.200	+.271	+.212	+.166	+.104
	+.014	-.022	-.021	.000	+.011	+.004
-1	+.104	-.012	-.017	+.026	+.057	+.018
	+.013	+.175	+.236	+.142	+.148	+.099
	-.066	-.116	-.108	-.062	-.029	-.016
-2	+.154	+.073	+.061	+.072	+.065	+.017
	+.044	+.121	+.159	+.047	+.108	+.081
	-.126	-.184	-.173	-.113	-.065	-.034
-3	+.162	+.146	+.133	+.101	+.051	+.006
	+.077	+.045	+.054	-.046	+.054	+.054
	-.150	-.204	-.196	-.140	-.088	-.047
-4	+.133	+.193	+.180	+.109	+.022	-.011
	+.088	-.043	-.060	-.107	-.004	+.023
	-.112	-.148	-.154	-.126	-.089	-.051
-5	+.085	+.192	+.181	+.093	-.008	-.023
	+.040	-.133	-.153	-.092	-.050	-.005
	+.010	+.013	-.019	-.056	-.057	-.041
-6	+.049	+.120	+.110	+.050	-.013	-.013
	-.119	-.212	-.188	+.050	-.065	-.020

NOTE : The strain rate components are in the order $\dot{\epsilon}_x$
$\dot{\epsilon}_y$
$\dot{\gamma}_{xy}$

(compression is negative)

TABLE 3-6

STRAIN RATES (SECONDS^{-1}). TEST NO. W8

Depth below original soil surface (inches)

Horizontal distance from wheel axis (inches). Direction of wheel travel →	0.7	1.7	2.7	3.7	4.7	5.7
+6	-.138 +.542 -.515	-.132 +.090 -.784	-.028 -.135 -.699	+.031 -.175 -.567	-.030 -.104 -.198	+.014 -.024 -.204
+5	+.062 -.054 -.264	+.129 -.132 -.477	+.167 -.236 -.434	+.152 -.282 -.329	+.069 -.229 -.121	+.055 -.078 -.099
+4	+.200 -.378 -.140	+.296 -.270 -.221	+.286 -.290 -.180	+.222 -.316 -.099	+.130 -.265 -.036	+.080 -.099 -.001
+3	+.275 -.494 -.099	+.371 -.333 -.020	+.332 -.300 +.043	+.244 -.292 +.102	+.157 -.237 +.047	+.088 -.095 +.081
+2	+.295 -.461 -.101	+.366 -.332 +.127	+.313 -.272 +.218	+.223 -.229 +.257	+.151 -.169 +.118	+.083 -.076 +.141
+1	+.265 -.338 -.113	+.293 -.279 +.220	+.240 -.210 +.331	+.165 -.142 +.355	+.120 -.084 +.168	+.066 -.048 +.177
0	+.196 -.175 -.109	+.169 -.188 +.262	+.128 -.125 +.376	+.083 -.046 +.387	+.069 +.001 +.192	+.040 -.019 +.186
-1	+.101 -.017 -.078	+.017 -.075 +.257	-.004 -.026 +.352	-.012 +.044 +.354	+.007 +.069 +.188	+.010 +.006 +.169
-2	-.006 +.106 -.020	-.014 +.042 +.210	-,135 +.074 +.267	-.104 +.117 +.262	-.057 +.111 +.156	-.022 +.023 +.129
-3	-.106 +.173 +.048	-.260 +.145 +.128	-.239 +.160 +.136	-.176 +.162 +.128	-.109 +.121 +.103	-.048 +.030 +.075
-4	-.179 +.183 +.088	-.319 +.212 +.017	-.287 +.214 -.017	-.207 +.175 -.025	-.137 +.103 +.040	-.064 +.028 +.015
-5	-.201 +.145 +.045	-.274 +.222 -.114	-.245 +.214 -.156	-.176 +.150 -.159	-.125 +.067 -.016	-.062 +.019 -.035
-6	-.145 +.097 -.164	-.079 +.148 -.256	-.077 +.139 -.237	-.056 +.089 -.228	-.056 +.033 -.041	-.034 +.010 -.057

NOTE : The strain rate components are in the order $\dot{\epsilon}_x$, $\dot{\epsilon}_y$, $\dot{\gamma}_{xy}$

(compression is negative)

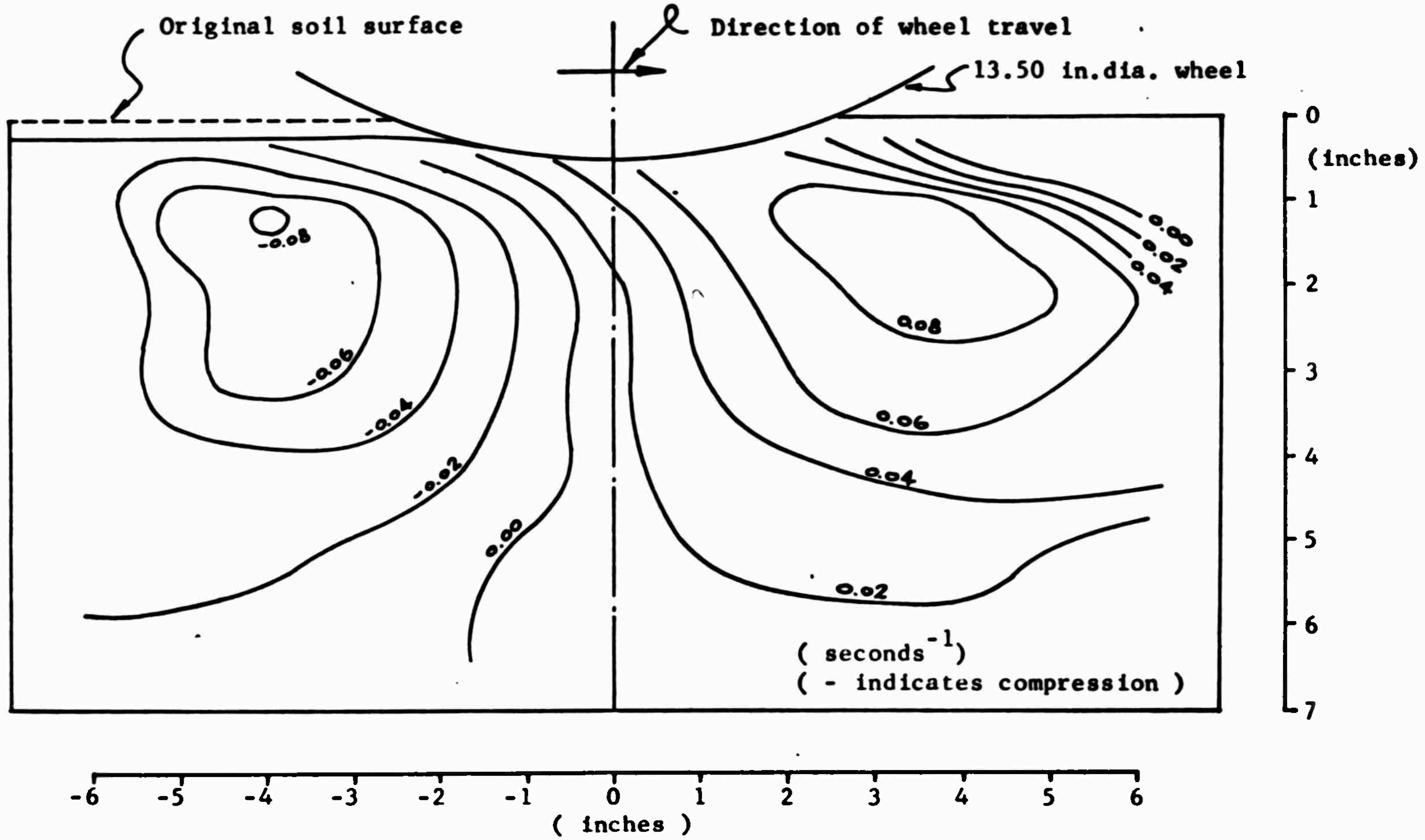

Figure 3.1

X-component of Strain-rate ($\dot{\epsilon}_x$), Test No. W 6

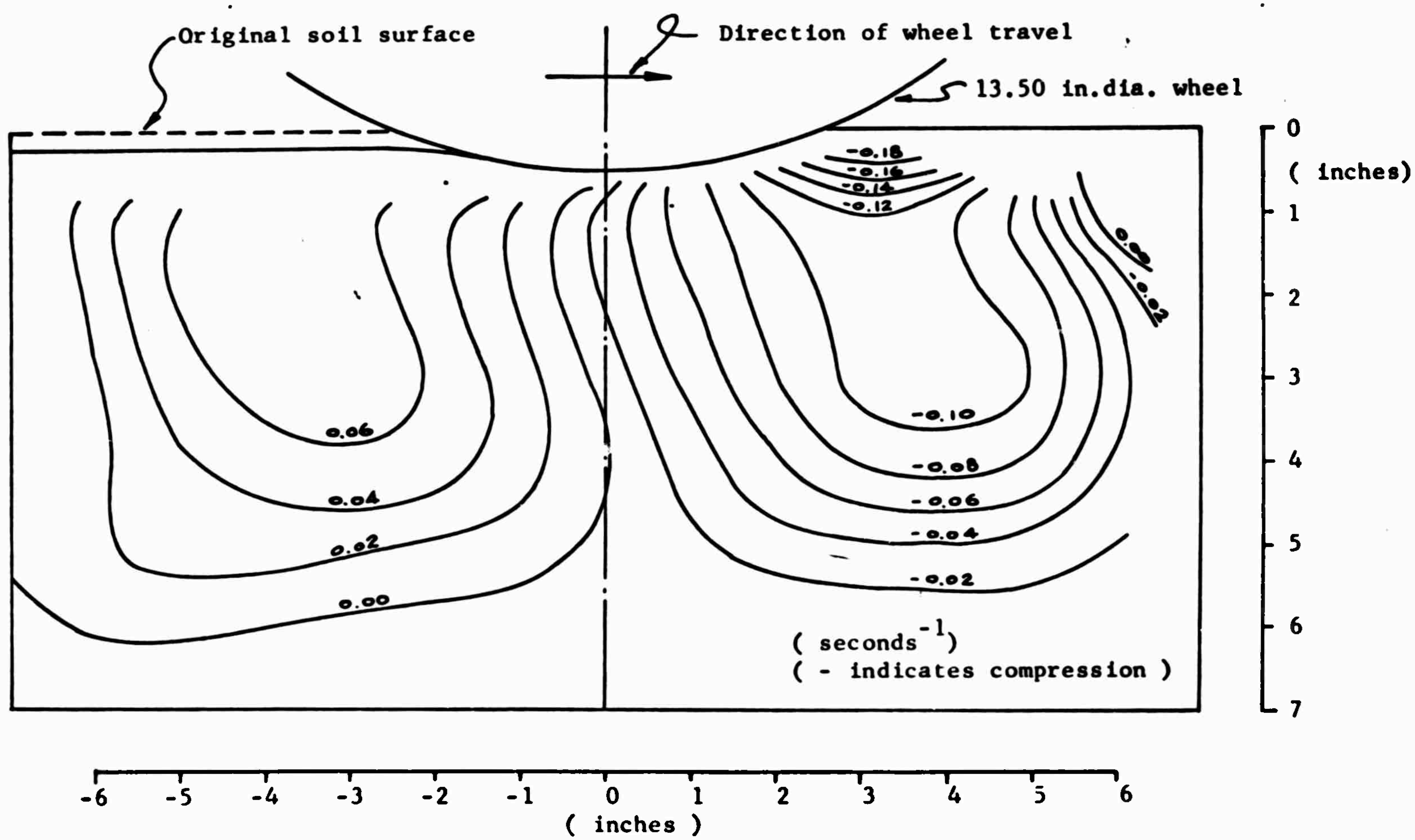

Figure 3.2

Y-component of Strain-rate ($\dot{\epsilon}_y$), Test No. W 6

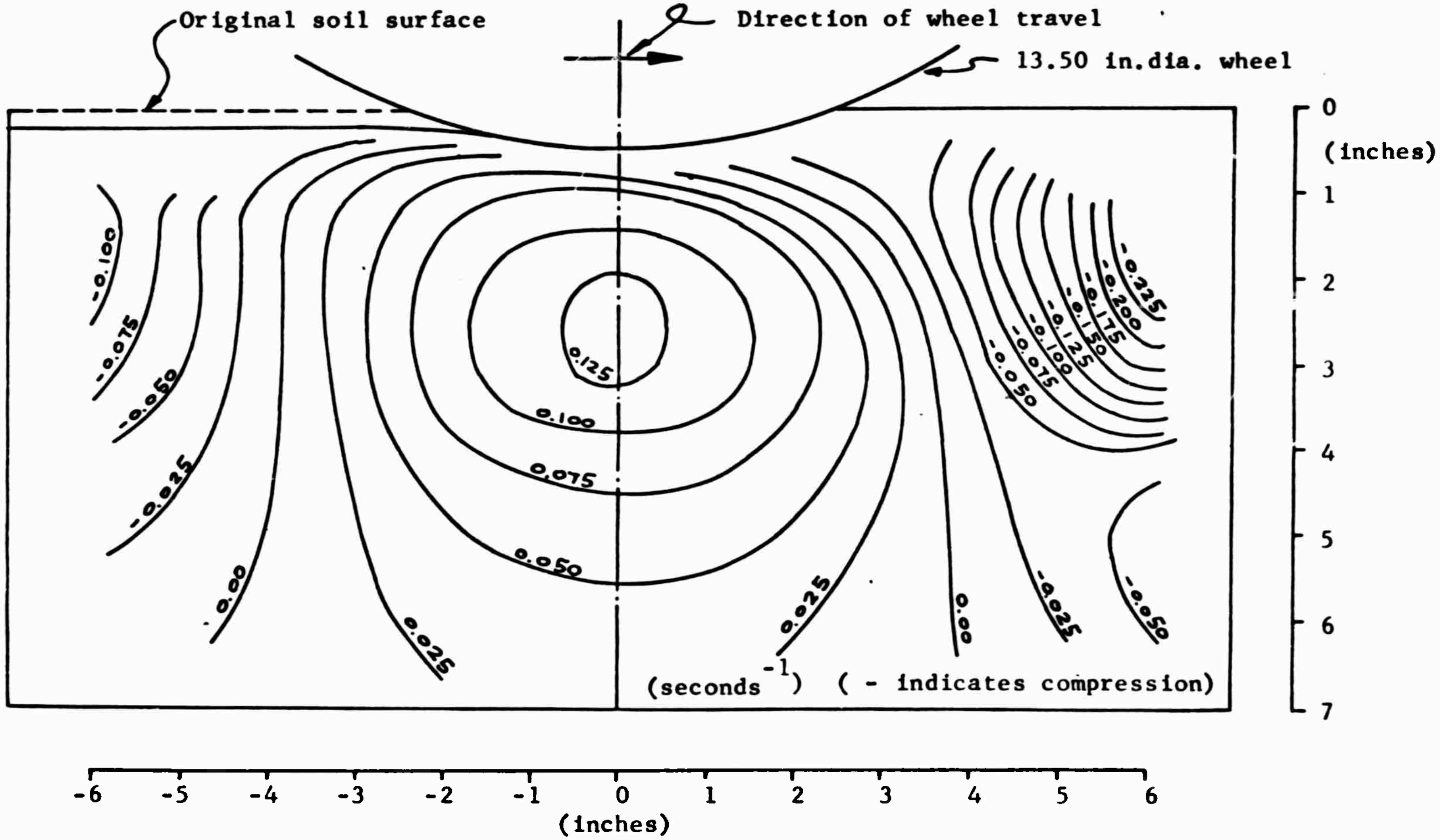

Figure 3.3

Shear Strain-rate ($\dot{\gamma}_{xy}$), Test No. W 6

Test No.	Wheel Data			Test Data				X-Ray Data			Soil Data (water content in %)
	Radius (inches)	Width (inches)	Total Weight (lbs)	Angular Velocity (revs/sec)	Carrage Velocity (in/sec)	Drawbar Pull (lbs)	Sinkage (inches)	S.O.D. (inches)	S.F.D. (inches)	Depth of Optical Center (inches)	
W3	6.75	3.75	54	.073	3.29	7.3	.33	14.2	18.8	2.0	51.9
W4	6.75	3.75	54	.130	5.55	6.2	.46	12.0	16.2	1.8	49.0
W5	6.75	3.75	34	.136	5.98	3.5	.33	14.0	18.75	2.2	51.2
W6	6.75	3.75	34	.073	3.97	7.5	.49	14.1	18.6	2.5	55.7
W7	6.75	3.75	34	.160	8.39	5.5	.49	14.1	18.6	2.4	55.7
W8	6.75	3.75	54	.144	8.85	13.7	.74	14.1	18.6	2.3	55.7

TABLE 3-7

TEST PARAMETERS AND SOIL DATA

REFERENCES

Yong, R.N. and Osler, J.C. (1966) "On the Analysis of Soil Deformation Under a Moving Rigid Wheel", Proc. 2nd Int. Conf. I.S.T.V.S., Quebec, pp 339-352.

Yong, R.N., Boyd, C.W. and Webb, G.L. (1967) "Experimental Study of Behaviour of Sand Under Moving Rigid Wheels", Soil Mechanics Series No. 20, Report No. D.Phys.R.(G) Misc 27, Directorate of Physical Research, Defence Research Board, Ottawa, Canada.

Yong, R.N. and Fitzpatrick-Nash, J.D. (1968) "Drawbar Pull Prediction from Energy Losses in Wheel-Clay Interaction", Soil Mechanics Series No. 22, report to Defence Research Telecommunications Establishment, Report DRTE (Geophysics) 29, Defence Research Board, Ottawa, Canada.

Yong, R.N., Fitzpatrick-Nash, J.D., and Webb, G.L. (1968) "Response Behaviour of Clay Soil Under a Moving Rigid Wheel", Soil Mechanics Series No. 23, report to Defence Research Telecommunications Establishment, Report DRTE (Geophysics) 30, Defence Research Board, Ottawa, Canada.

Yong, R.N. and Webb, G.L. (1968) "Energy Considerations in Wheel-Clay Soil Interaction", Soil Mechanics Series No. 25 (in press), Report to Defence Research Telecommunications Establishment, Defence Research Board, Ottawa, Canada.